

Using a geometric-optical model to calculate the bidirectional and hemispherical reflectance of forested slopes

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ABSTRACT

The Li-Strahler geometric-optical model has been used with some success to simulate the bidirectional and hemispherical reflectance of forest canopies. Although the canopies modeled thus far may have contained trees of widely varying heights, the underlying terrain has always been represented as level ground. Recently, however, the model has been extended to accommodate sloping terrain in its computation of the forest Bidirectional Reflectance Distribution Function (BRDF) and spectral surface albedo. With the model accommodating topography, it has been possible to compute and compare the reflective character of realistic forest canopies on a variety of slopes and aspects.

1. INTRODUCTION

The Li-Strahler geometric-optical model treats a forested scene as an assemblage of spheroidal tree crowns with a distribution of heights^{1,2,3,4,5,6,7}. Geometric-optics and Boolean set theory are used to determine the areal proportions of shadowed and sunlit canopy and shadowed and sunlit background associated with a particular view angle under given illumination conditions. These areal proportions are weighted by independently-determined characteristic spectral signatures for each of the shadowed or sunlit components and are used to determine the spectral bidirectional reflectance factor of the canopy. The model captures both the "hotspot" effect (the peak in directional reflectance in the backscatter direction that occurs when the viewer of a forested canopy is in the same angular position as the sun and all visible portions of the scene are illuminated and unshadowed) and mutual shadowing (a scene brightening effect which occurs at high view or solar zenith angles where only the tree tops are illuminated and any shadows are lost in the lower part of the canopy and obscured by other tree crowns).

This model has recently been extended to accommodate forests located on sloping terrain. The geometric relationships among the illumination angle, the view angle, and all of the tree shape characteristics are transformed into the coordinate system of that slope, so that the problem reduces to that of mutual shadowing on a flat surface. The resultant BRDF is then transformed back into true space, where a hemispherical integration takes place to produce an albedo. The computations assume that the model domain (simulating a sensor field of view or pixel) is the same as or smaller than the slope since the geometric-optical model produces direct beam results and does not accommodate the effects of diffuse radiation reflecting off of adjoining terrain.

2. TOPOGRAPHIC TRANSFORMATIONS

Several transformations in coordinate space are required to apply the Li-Strahler geometric-optical model to canopies on sloping terrain. Given a solar zenith angle θ_i , a view zenith angle θ_v , a solar azimuth ϕ_i , a slope elevation θ_s , and a slope aspect ϕ_s (Figure 1a), the first transformation replaces θ_i , θ_v , and θ_s with θ'_i , θ'_v , and θ'_s , where the tree crown elongated spheroids are replaced with spheres which cast the same shadow area (Figure 1b). The θ'_s is given as:

$$\theta'_s = \frac{\pi}{2} - \tan^{-1}\left(\frac{b}{R} \tan\left(\frac{\pi}{2} - \theta_s\right)\right) . \quad (1)$$

The tree crowns are now represented by spheres (the trunks are ignored). A second transformation will convert the entire scene to slope coordinates (Figure 1c) where the Y axis remains the same and the scene is rotated about it. The slope normal becomes the Z' axis, and the X' axis runs along the surface of the slope. The slope ϕ_s is set to zero. The solar angles are then recalculated in relation to these slope coordinates:

$$\phi'_i = \phi_i - \phi_s \quad (2)$$

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$$x' = \cos\phi'_i \sin\theta'_i \cos\theta'_s - \cos\theta'_i \sin\theta'_s \quad (3)$$

$$y' = \sin\phi'_i \sin\theta'_i \quad (4)$$

$$z' = \cos\phi'_i \sin\theta'_i \sin\theta'_s + \cos\theta'_i \cos\theta'_s \quad (5)$$

resulting in transformed solar angles of:

$$\theta''_i = \cos^{-1} z' \quad (6)$$

$$\phi''_i = \tan^{-1} \frac{y'}{x'} \quad (7)$$

Once the illumination angles have been transformed, the scene can be treated as a flat surface and the BRDF can be calculated in the usual manner with the principal plane located where $\theta''_v = \phi''_i$ or $\theta''_v = \phi''_i + \pi$. This will result in a reflectance for each view zenith θ''_v and view azimuth ϕ''_v . These reflectances can then be associated with coordinates in true space by transforming them back with:

$$x' = \sin\theta''_v \cos\phi''_v \quad (8)$$

$$y' = \sin\theta''_v \sin\phi''_v \quad (9)$$

$$z' = \cos\theta''_v \quad (10)$$

$$\phi'_v = \tan^{-1} \left(\frac{y' \sin\theta'_s + \cot\theta'_s \cos\theta'_s y'}{z' + \cot\theta'_s x'} \right) \quad (11)$$

$$\theta'_v = \sin^{-1} \left(\frac{y'}{\sin\phi'_v} \right) \quad (12)$$

Finally, by adding the slope aspect, the angles are again related to true compass directions and, by transforming the crown spheres back into elongated spheroids, each reflectance is associated with a true view zenith (θ_v) and true view azimuth (ϕ_v). At this point it is possible to perform a hemispherical integration and produce a direct beam albedo for the forested slope.

3. SIMULATIONS

To explore the effects of the new topographic transformations on canopy BRDFs and albedos, model bidirectional and hemispherical reflectances were calculated for a scene that realistically simulates an orographically complex region of the Sierra Nevada. Extensive field data from this region⁸ were available to initialize the geometric-optical model for three forest types (hardwoods, mixed conifers, and pines). The distribution of landcover types over the area is displayed in Figure 4a. Digital terrain data of the area (at a 3 arc second resolution) were used to determine slope facets and aspects. Spectral BRDFs were modeled for each of the landcover/slope/aspect facets displayed in Figure 4b. A solar zenith angle of 42.62° and a solar azimuth angle of 81.9° (counterclockwise from south) were used in the calculations. Under these illumination conditions, topographic shading (with its obvious impacts on surface albedo) was not a problem (<2% of the scene).

The BRDF describes the intrinsic character of the canopy surface under a given solar illumination. As revealed in the spectral BRDFs of the conifer forest on facets of flat terrain (Figures 2a-b), the hotspot peak occurs when the viewing position approaches the illumination angle. Its shape is governed by the brightness contrast between tree crown and background and by the shape and density of the crowns and the rapidity with which the shadows they cast are revealed when the viewing and illumination geometry diverge. Opposite the hotspot (in the forward scattering direction), increasingly large areas of shadow (with lower reflectances) are viewed. The upturned bowl-shape is produced when the proportion of viewed shadows is reduced by the obscuring of these shadows by nearby crowns (*i.e.*, the scene brightens at the large view angles, as only unshadowed crown tops are viewed). This mutual shadowing occurs at either high illumination or high viewing zenith angle (or both).

Once a canopy is draped over a slope, the shape of the BRDF changes. Figures 3a-d depict the near-infrared spectral BRDFs associated with the steepest slopes (30° and higher). The hotspot still occurs at the same location, regardless of slope. The forward scatter radiation, however, is forced into a skewed direction governed by the elevation and aspect of the slope. Therefore the principal plane may now veer along from the hotspot into the shadowing region. The crown shadowing is governed by the difference between the slope normal and the solar angle rather than the solar angle itself. Figures 3a-d reveal the BRDF distortion that occurs as the aspect on the slopes is swiveled through the compass directions. The view angles engulfed by the slope mass are of course not represented. Similarly, the reflectances from view angles that would be below the horizontal are set to zero. As stated earlier, the model assumes the pixels are smaller or the same size as the slope, and no additional view factor radiation from nearby terrain is incorporated.

Hemispherical reflectances (or direct beam surface albedos) were computed from each BRDF. Spectral results were combined to produce full spectrum albedos for each forest type⁹. Each of the landcover/slope/aspect facets in Figure 4b was associated with the appropriate modeled albedo and the resulting albedo image is displayed in Figure 5b. The flat terrain hemispherical reflectance is the largest albedo value associated with each canopy. This occurs because the flat case is the only one where a nonzero reflectance value is associated with each and every possible view angle in the integrating sphere. The albedo is a rather consistent value, affected only slightly by the gentler slopes (for instance there is only a 12% variation in albedo on 16° slopes with differing aspects). On the steepest slopes (30° and higher), the albedo is more sensitive to aspect. However, these slopes represent less than 10% of the scene. The slopes that face away from the sun receive less direct solar radiation, but are associated with larger albedos than the slopes that face the sun. This occurs because of changes in the shadowing patterns and an increase in mutual shadowing. The sun, when it is regarded in slope coordinates, achieves very large solar zenith angles on slopes facing away from the sun. and in general, mutual shadowing usually increases (enough so that the overall hemispherical reflectance also increases) as the solar zenith angle increases.

The relative stability of the modeled albedos suggest that the differences in hemispherical reflectance due to species signature and tree shape, height and density are more important than those due to slope and aspect. If the landcover distribution shown in Figure 4a is draped over level terrain instead of realistic complex terrain, then the albedos occur as displayed in Figure 5a. A comparison of Figures 5a and 5b reveal only minimal differences.

4. CONCLUSIONS

In the case of forest canopies, the sloping surface significantly changes the pattern of sunlight and shadows being cast by and on individual trees and therefore changes both the bidirectional reflectance distribution function and the hemispherical reflectance associated with that canopy. When the Li-Strahler geometric-optical model is used to simulate conifer canopies on gentle to moderate slopes, the hemispherical reflectances remain rather consistent although the shapes of the BRDFs do change somewhat. It is only on the steepest slopes (30° and higher), that the shape of the BRDF becomes quite distorted and there is a distinct variation in the albedo values. Overall, the largest albedo values are associated with flat terrain. When comparing slopes with the same elevation angle but different aspects, the slopes facing away from the sun exhibit increased mutual shadowing and therefore display larger albedos than do the sunward facing slopes. These simulations indicate that, although an assumption of flat terrain may result in somewhat of an overestimation of surface albedo, such an assumption is not unreasonable since the impact of gentle to moderate slopes on surface albedo is small. This would suggest that the albedo of a forest canopy which exhibits consistent type and structure characteristics over a large region may also exhibit a fairly uniform albedo over this same area even if the underlying terrain is undulating. However, in regions of more rugged terrain, forest albedos will vary significantly since the values will be affected not only by changes in the shadowing geometries of the canopy, but also by terrain shadowing effects and the receipt of scattered radiation from adjoining slopes. Neither of the latter two macro-level three-dimensional effects is handled by the Li-Strahler geometric-optical model.

5. REFERENCES

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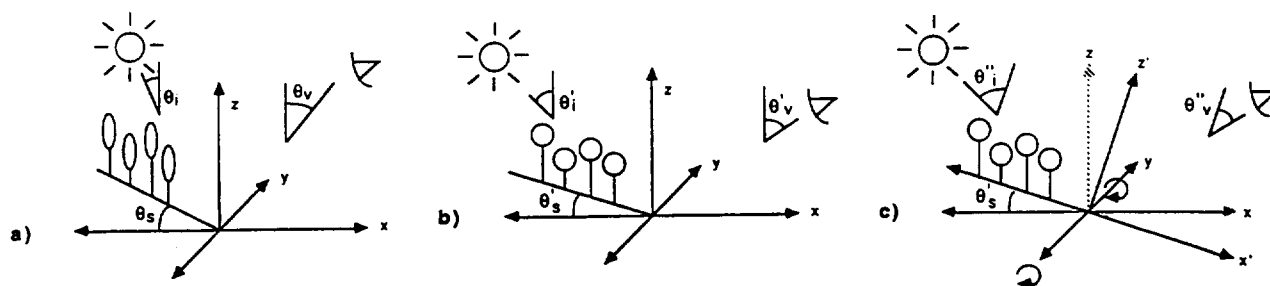


Figure 1. Schematic depicting the coordinate system transformations required so that the geometric-optical model can accommodate a sloping surface.

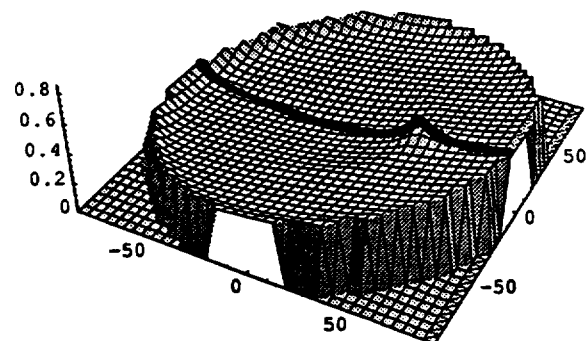
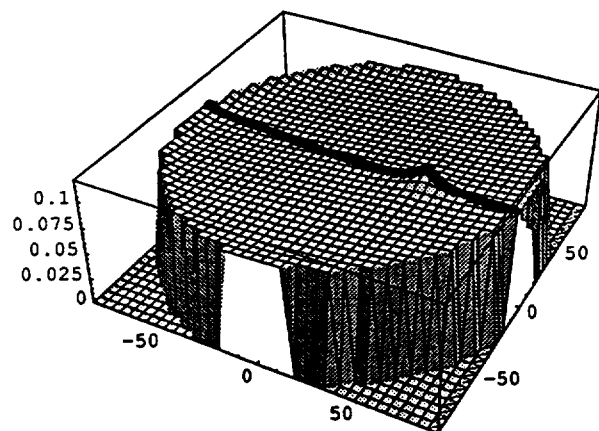


Figure 2. Red (a) and NIR (b) BRDF simulations of a mixed conifer canopy on level terrain. Each three-dimensional BRDF is displayed in a rectangular coordinate system where each view angle in the hemisphere is taken as a pair of polar coordinates and transformed onto the x - y plane as a vector of unit length. Corresponding reflectances are then plotted along the z axis.

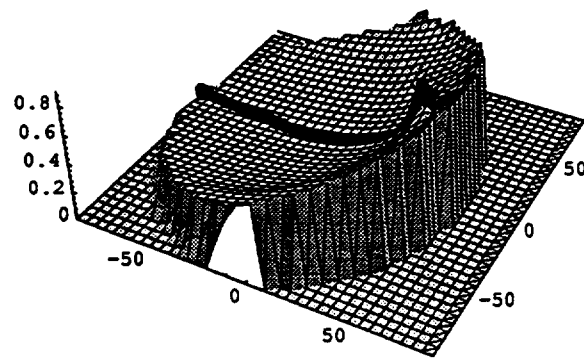
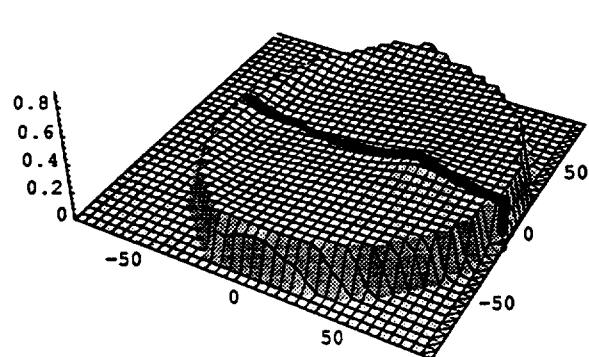
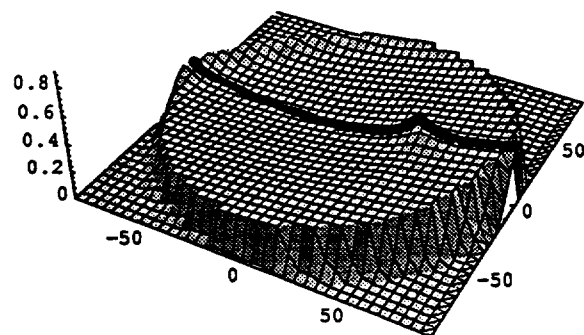
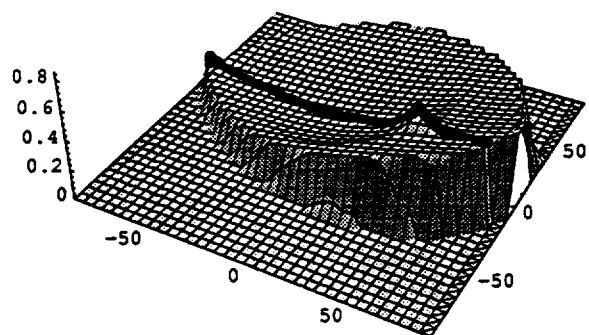


Figure 3. Near-infrared BRDF simulations of a mixed conifer canopy on (a) a north facing 30° slope, (b) a south facing 30° slope, (c) an east facing 30° slope and (d) a west facing 30° slope.

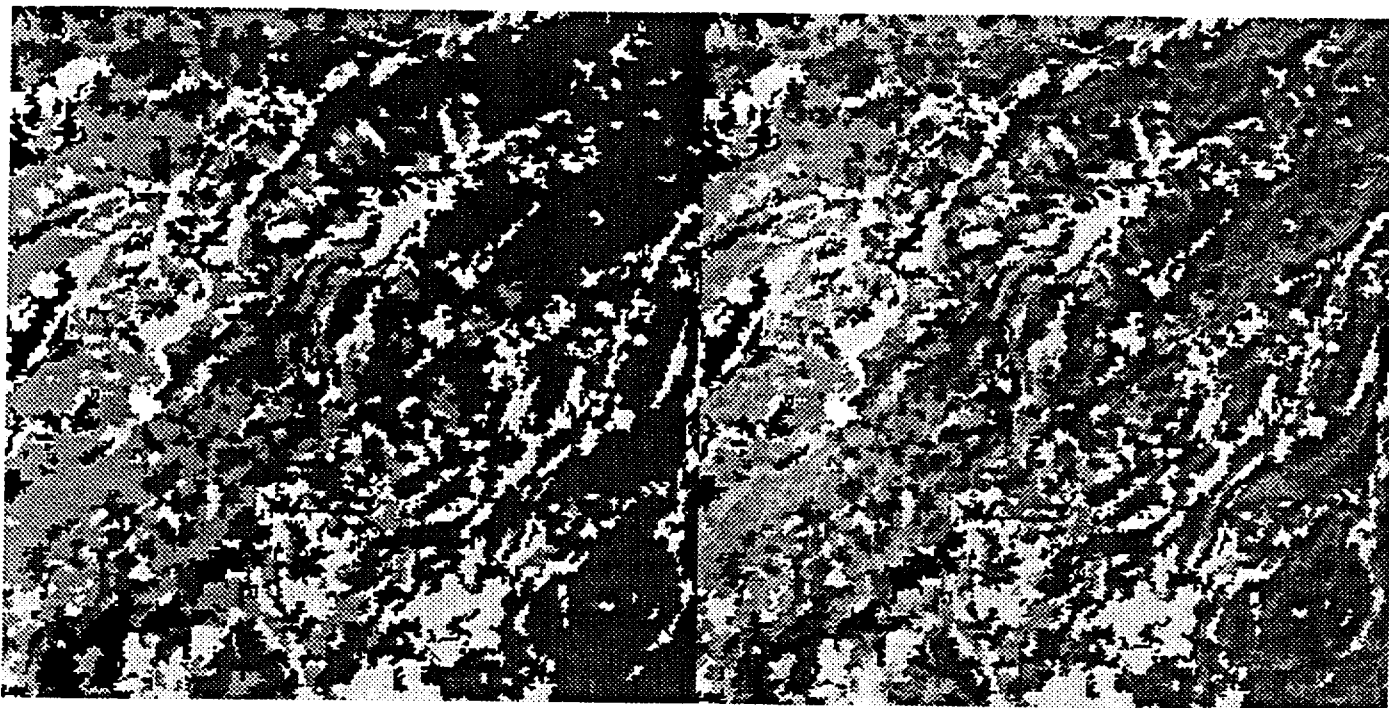


Figure 4. The distribution of landcover types (left) and the distribution of landcover/slope/aspect facets (right). The darkest shades are the hardwoods, the medium grey shades are the mixed conifers and the light grey shades are the pines, while non-modeled landcovers such as water, barren, and brush are in white.

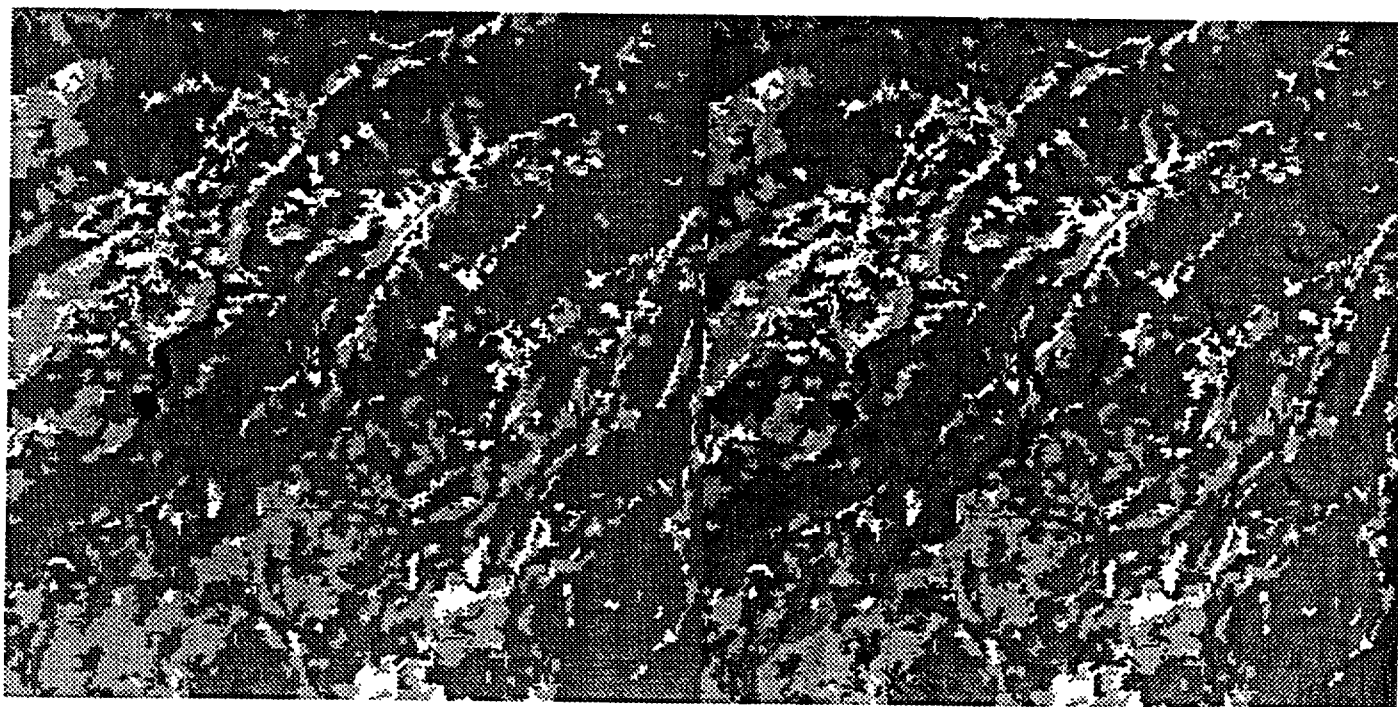


Figure 5. Modeled albedos displayed as images. The albedos from forest on level terrain (left) are 0.20 for hardwoods, 0.16 for mixed conifer and 0.14 for pines. The albedos from forests on sloping terrain (right) range from 0.20 to 0.95. The non-modeled barren and brush landcovers are white and water is black.